DYNAMIC PROPERTIES OF FROZEN SAND UNDER SIMULATED EARTHQUAKE LOADING CONDITIONS

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SUMMARY

Cyclic triaxial tests on coarse frozen sand specimens prepared at three sand contents were conducted under simulated earthquake loading conditions. The test results indicate that dynamic Young's modulus decreases with increasing axial strain amplitude and increases, in general, with increasing confining pressure, sand content and frequency and descending temperature. The test results also indicate that damping ratio increases with increasing sand content and ascending temperature, and decreases with increasing frequency. The effect of confining pressure on damping ratio is not great. There appears to be no well-defined relationship between damping ratio of frozen sand and axial strain amplitude.

INTRODUCTION

Early research to evaluate the dynamic properties of frozen soils was associated with engineering problems in Alaska and other cold regions of the world arising in connection with (1) vibrating machinery placed on or in frozen ground deposits, (2) geophysical exploration of frozen ground deposits and (3) excavation of frozen ground deposits by blasting (1). Later, the need to evaluate the dynamic properties of frozen soils under simulated earthquake loading conditions was recognized in environmental situations where permafrost deposits existed in highly seismic regions of the world. Examples of areas with substantial permafrost and high seismicity include the central portion of Alaska (2, 3) and the Baikal region in the U.S.S.R. (4, 5).

More recently, however, the demand for energy has focused attention on the need to evaluate the dynamic properties of frozen soils under earthquake loading conditions even in temperate climates. Underground liquefied natural gas storage tanks are being constructed in highly seismic areas of the world such as Japan. A zone of frozen soil several meters thick can develop around the tank. An accurate analysis of the tank requires the determination of the dynamic properties of the frozen soil surrounding the tank under simulated earthquake loading conditions.

In response to the need to evaluate the dynamic properties of frozen soils under simulated earthquake and low frequency loading conditions, the dynamic properties of a coarse-grained frozen sand have been evaluated with cyclic triaxial test equipment. The results of this test program are reported herein.

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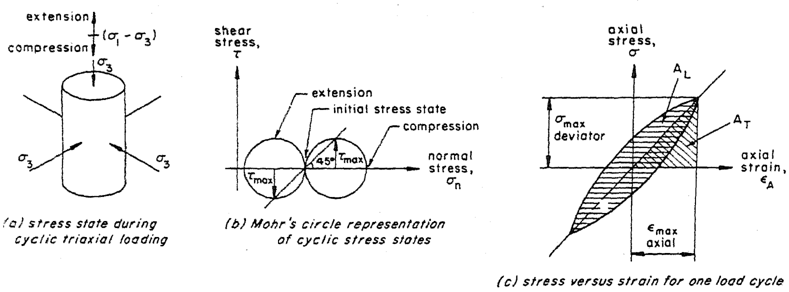

Figure 1 - STRESS STATE AND STRESS VERSUS STRAIN FOR CYCLIC LOADING TEST

DYNAMIC PROPERTY DETERMINATION AND CYCLIC TRIAXIAL TEST SYSTEM

The dynamic properties of frozen sand under simulated earthquake loading conditions can be evaluated in a cyclic triaxial test. In the cyclic triaxial test a cylindrical test specimen is placed in a triaxial cell and confined to an initial isotropic stress state, as shown in Figs. 1a and 1b. An axial load is cycled on the specimen causing a reversal of shear stresses which are a maximum on 45 degree planes. During the test, the cyclic axial load and specimen deformation are recorded. The axial (deviator) stress and strain in the specimen are determined with a knowledge of the cross-sectional area and length of the specimen. Typical test results expressed in these terms for one cycle of loading are shown in Fig. 1c. From the results shown in Fig. 1c, dynamic Young's modulus, E_d, and damping ratio, λ, may be calculated from Eqs. (1) and (2) as follows:

$$E_d = \frac{\sigma_{max.\ deviator}}{\varepsilon_{max.\ axial}} \quad (1); \qquad \lambda = \frac{A_L}{4\pi\ A_T} \quad (2)$$

with the terms as defined in Fig. 1c. A_L represents the total dissipated energy per cycle and A_T represents the work capacity per cycle.

The cyclic triaxial test system employed in the test program has been described in detail by Vinson, et al. (6). The test system represents a coupling of existing equipment to evaluate the dynamic properties of unfrozen soils with existing temperature control equipment to evaluate the static properties of frozen soils. The test system consists of four basic components: (1) a triaxial cell surrounded by a circulating coolant in a cold bath; the triaxial cell contains the test specimen and noncirculating coolant; (2) an electrohydraulic closed-loop test system which applies a cyclic axial load to the piston loading rod of the triaxial cell, (3) a refrigeration unit that maintains the temperature of the system at a given level; and (4) output recording devices.

MATERIAL DESCRIPTION AND TEST SPECIMEN PREPARATION

The material tested was a uniform coarse sand with particle diameters between 3.35 and 4.75 mm (0.13 and 0.19 in.). The frozen cylindrical test specimens were 71 mm (2.8 in.) in diameter and 168 mm (6.6 in.) in height. All of the specimens tested were reconstituted materials artificially frozen in the laboratory. The test specimens were prepared at sand contents (S) of 24, 42, and 59% (by volume). A detailed description of the test specimen preparation procedures for the dense coarse-grained materials (sand content of 42 and 59%) and the loose coarse-grained material (sand content of 24%) is given by Vinson, et al. (6).

When cyclic triaxial tests are performed on unfrozen test specimens, the specimen is not allowed to develop a tensile state of stress during the extension cycle of loading. This is due to the low or nonexistent tensile strength of unfrozen soils. In contrast to this, frozen soils can be subjected to tensile stresses during the extension cycle of loading. To allow for this possibility, the test specimen must be coupled to the cap and base used in triaxial testing. Details of the coupling device used to develop possible tensile stresses during the extension cycle of loading are given by Vinson, et al. (6).

TEST PROGRAM AND RESULTS

Test Program. Strain-controlled cyclic triaxial tests were conducted on the frozen coarse-grained sand specimens. The specimens were tested at temperatures (T) of -1, -4, and -10°C (30.2, 24.8 and 14°F), confining pressures (σ_c) of 0, 350, and 1400 kN/m^2 (0, 50, and 200 psi), frequencies (f) of 0.05, 0.3, 1.0, and 5.0 cps, and over a range of axial strain amplitudes (ε_A) from 10^{-3} to $10^{-1.4}$%.

Each specimen was generally subjected to 10 cycles of loading at a given axial strain amplitude, confining pressure, and frequency of loading. The dynamic Young's modulus and damping ratio for each loading condition were determined at the 10th cycle using an algorithm on a minicomputer which was coupled to the test system.

Influence of Axial Strain Amplitude. The values of dynamic Young's modulus were plotted against the log of percent axial strain amplitude. Typical test results are shown in Fig. 2. The solid lines shown in Fig. 2 represent the least squares best fit line of the data set shown. The results indicate dynamic Young's modulus decreases with axial strain amplitude. The magnitude of the decrease varies from one test condition to another and does not follow a definite trend. The decrease in dynamic Young's modulus with increasing axial strain amplitude is similar to the behavior of unfrozen soils. Over the range of test conditions considered, the value of dynamic Young's modulus ranged from 1.4 to 21 GN/m^2 (2 x 10^4 x 10^6 psi).

It can be seen in the figure that there is "scatter" in the data points for a given test condition. It is believed the scatter was caused by (1) slight variations in the density of the specimens, (2) slight differences in the structural composition of the test specimens, particularly near the coupling, and (3) slight temperature differences between tests. Also, at the lower strain amplitudes of testing, the test system approached its limit of capacity both electronically and mechanically. Some variation in test results at this extreme of testing is to be expected.

Typical test results depicting the relationship between damping ratio and axial strain amplitude are shown in Figure 3. The solid lines represent the least squares best fit of the data set shown. The value of

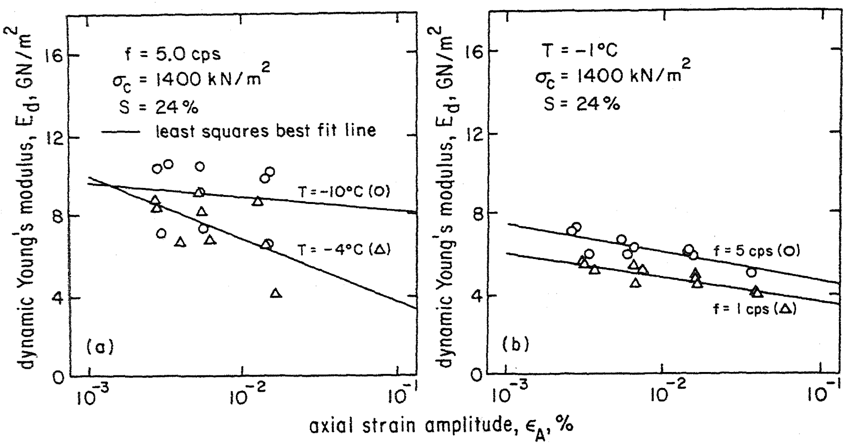

Figure 2 - DYNAMIC YOUNG'S MODULUS VERSUS AXIAL STRAIN AMPLITUDE

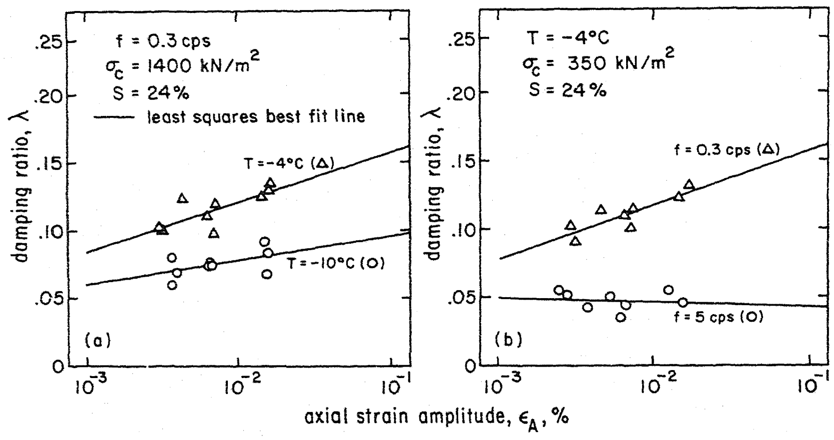

Figure 3 - DAMPING RATIO VERSUS AXIAL STRAIN AMPLITUDE

damping ratio may increase, decrease, or remain constant with increasing axial strain amplitude. Following a close examination of the data for all test conditions, it was concluded that no consistent relationship between damping ratio and axial strain amplitude exists. Over the range of test conditions considered, the value of damping ratio ranged from 0.01 to 0.31.

The relationship between dynamic Young's modulus and/or damping ratio can be established by interpolation of the results presented in Figs. 2 and 3, and similar results for all other test conditions considered in the program, at a specified axial strain amplitude. A strain amplitude of 10^{-2}% was selected for this purpose. Another strain amplitude could have been selected without significantly changing the conclusions reached in the following paragraphs.

Influence of Temperature. The relationship between dynamic Young's modulus

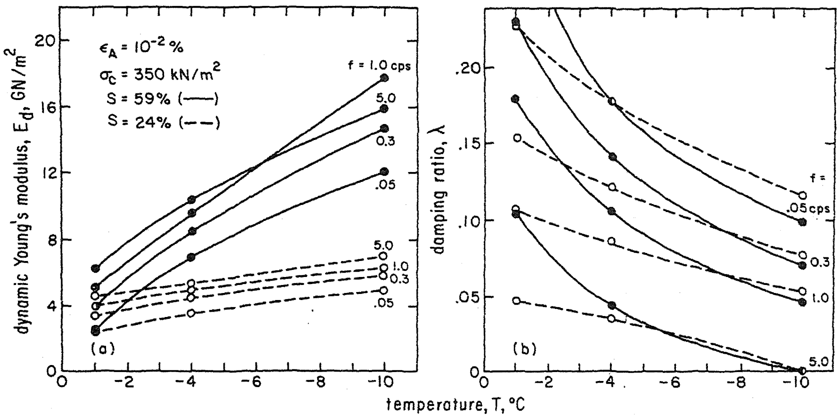

Figure 4 – DYNAMIC YOUNG'S MODULUS AND DAMPING RATIO VERSUS TEMPERATURE

and temperature is shown in Fig. 4a. Dynamic Young's modulus increases with descending temperature. The rate of increase is greater at higher sand contents. At a given sand content, the rate of increase is independent of frequency.

As shown in Fig. 4b, damping ratio decreases with descending temperature. The rate of decrease appears to be greater at higher sand contents. The rate of decrease at a given sand content appears to be independent of frequency.

The temperature dependence of the dynamic properties of frozen sand is possibly associated with the dependence of the dynamic elastic properties of cohesionless soils on increased intergranular contact stresses. It is well established that the dynamic Young's modulus of unfrozen cohesionless soils increases and the damping ratio decreases with increased stress at the contact points between particles. The ice in the voids of a frozen soil in which the soil grains are in contact must also increase the stress at the contact points owing to the adhesive-attractive bond it has with the particles. The adhesive-attractive bond is apparently temperature dependent; the lower the temperature, the greater the adhesive-attractive bond and the greater the stress at the contact points. Consequently, dynamic Young's modulus should increase and damping ratio should decrease with descending temperature. Further, the degree to which the dynamic properties are dependent on temperature should depend on the number of contacts. The greater the number of contacts or sand content, the greater the dependency.

Influence of Frequency. The relationship between dynamic Young's modulus and frequency is shown in Fig. 5a; the relationship between damping ratio and frequency is shown in Fig. 5b. Dynamic Young's modulus increases and damping ratio decreases with increasing frequency. The influence of frequency on the dynamic properties of frozen sand may be a reflection of the stress relaxation or creep tendencies of the material. Stress relaxation would tend to cause increasing stress reduction with time under a constant strain. It follows that for strain-controlled cyclic triaxial tests, as employed in the test program, a decrease in strain rate will result in a

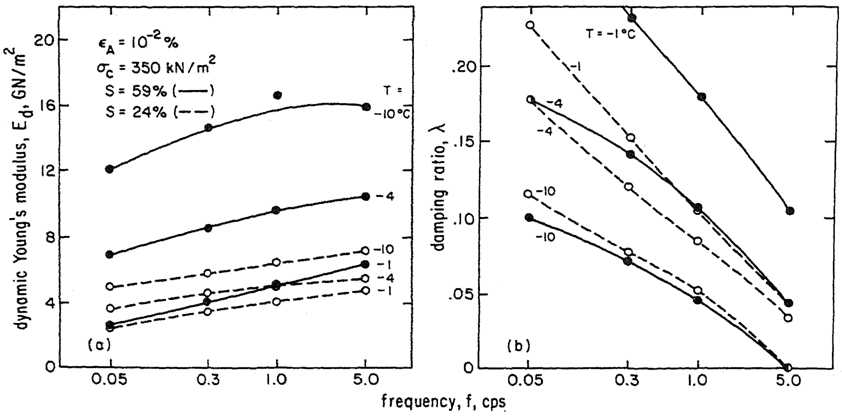

Figure 5 – DYNAMIC YOUNG'S MODULUS AND DAMPING RATIO VERSUS FREQUENCY

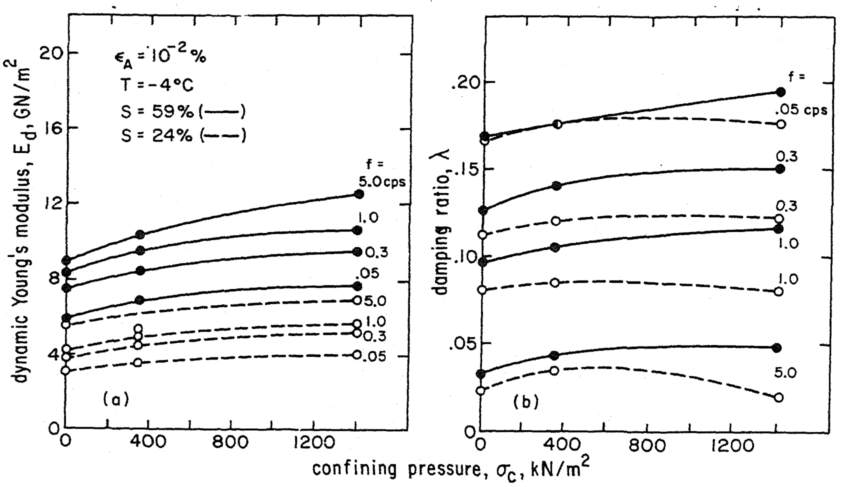

Figure 6 – DYNAMIC YOUNG'S MODULUS AND DAMPING RATIO VERSUS CONFINING PRESSURE

corresponding increase in stress reduction over a cycle of loading and, hence, a decrease in dynamic Young's modulus. Further, with a reduced strain rate, creep would tend to cause greater displacements between grains and, therefore, greater damping.

Influence of Confining Pressure. The relationship between dynamic Young's modulus and confining pressure is shown in Fig. 6a. Dynamic Young's modulus increases as the confining pressure increases. The rate of increase is apparently independent of the sand content and frequency of loading.

The relationship between damping ratio and confining pressure is shown in Fig. 6b. In general, damping ratio increases with increasing confining pressure. There are exceptions to this trend; for example, at the lowest sand content and highest frequency the damping ratio apparently decreases

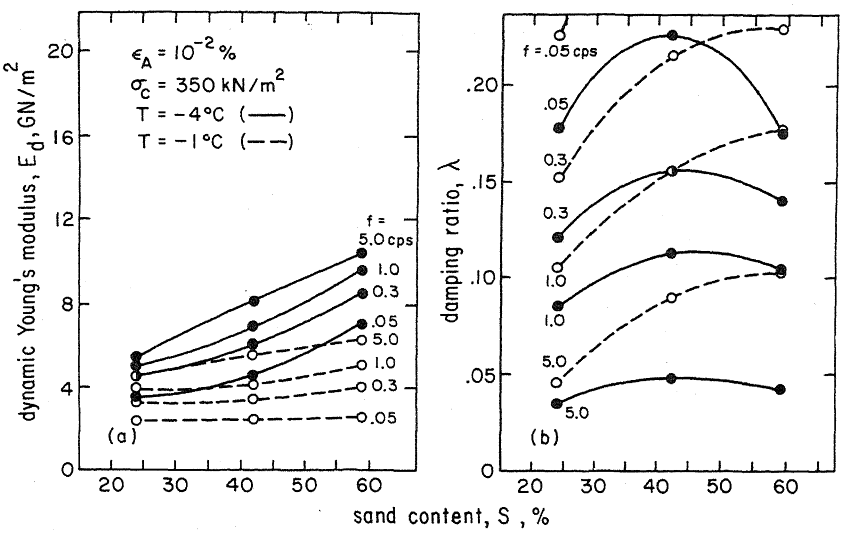

Figure 7 - DYNAMIC YOUNG'S MODULUS AND DAMPING RATIO VERSUS SAND CONTENT

with increasing confining pressure. Overall, the effect of confining pressure on damping ratio is not great.

Influence of Sand Content. The relationship between dynamic Young's modulus and sand content is shown in Fig. 7a. As would be expected, dynamic Young's modulus increases with increasing sand content. The rate of increase is dependent on temperature. At a colder temperature (-4°C) the rate of increase is greater. At a sand content of 24%, the sand particles are not in contact. At a sand content of 42%, the particles come into contact. Therefore, the rate of increase in the relationship between dynamic Young's modulus and sand content below 42% should be less than the rate of increase above 42%. In general, this is the case. However, the difference in the rates of increase is not as great as might be expected.

The relationship between damping ratio and sand content is shown in Fig. 7b. At a warmer temperature (-1°C) damping ratio increases with increasing sand content. This behavior would appear to be reasonable owing to the increase in interparticle friction with increasing sand contact. At colder temperatures (-4°C) damping ratio increases then decreases with increasing sand content. It is not possible to explain this at this time.

COMPARISON OF CYCLIC TRIAXIAL TEST RESULTS FOR TWO SANDS

The results from cyclic triaxial tests conducted on a uniform medium sand with particle diameters between 0.42 and 0.85 mm (0.017 and 0.034 in.) have previously been reported (7). It is instructive to compare the results obtained in the previous study to those obtained in the present study. Fig. 8a shows the relationship between dynamic Young's modulus and temperature for the two sands at three sand contents. In general, it appears dynamic Young's modulus is slightly greater for the medium sand.